Spintronics: Transport Phenomena in Magnetic Nanostructures

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Summary. Nanotechnology plays a decisive role in information technology. However the rapid increase (doubling of the Internet traffic every 6 months, of the wireless capacities every 9 months and of the magnetic information storage every 15 months) cannot be compensated by a simple downscaling of the semiconductor devices, as it was done in the past 30 years. To keep up with the demands, completely new devices have to be invented, operating on the nanoscale and exploit quantum effects. A very promising option is to use the spin of the electron in addition to its charge for information transmission and storage, i.e. going from the conventional electronics to spintronics. The foundations of this technique and the broadest application areas today, exploiting the giant magnetoresistance and the tunneling magnetoresistance are discussed from the experimental and theoretical point of view.

3.1 Introduction

The information technology revolution is based on an exponential rate of technological progress. For example, Internet traffic doubles every 6 months, wireless capacity doubles every 9 months, and magnetic information storage capacity doubles every 15 months. Moore’s law which indicates that the performance of semiconductor devices doubles every 18 month has been valid for three decades. But, fundamental laws of physics limit the shrinkage of semiconductor components on which Moore’s law is based, at least on current technologies. The continuation of the information technology revolution relies on new ideas for information storage and processing, leading to future applications. One option is to look for mechanisms that operate at the nanoscale and exploit quantum effects [1]. Nanotechnology covers a wide range of different technologies involved in the investigation, manipulation and control of matter on the very small scale, atom-by-atom and molecule-by-molecule. Such technology opens the possibility to develop materials and products with ‘nanoscale’ structures or to build devices and systems the same size as biological cells with highly desirable properties.
For a long time the charge of the electron was used to process and store information. But the electron has an additional degree of freedom – the spin. To exploit the spin for new information processing techniques and to integrate it into the traditional electronics, this is the vision of the emerging field of spin electronics or spintronics. Reviews with a broader scope than this lecture are given in [2–4]. Here the focus will be given to the effects of giant magnetoresistance and tunneling magnetoresistance.

In the field of metallic systems layered structures of magnetic and non-magnetic materials dominated the common interest. In these multilayers ferromagnetic layers are separated by non-magnetic spacer layers. The phenomenon of interlayer exchange coupling (IEC), discovered 1986 by Grünberg et al., favors one relative orientation of the magnetization direction of the ferromagnetic layers [5]. That is, forced by the exchange interaction mediated by the conduction electrons of the non-magnetic spacer layer, the moments of adjacent magnetic layers are aligned parallel or antiparallel in zero magnetic field. The sign and strength of the coupling are mainly determined by the material and the thickness of the non-magnetic spacer layer [6,7].

Investigating the transport properties of these structures a new phenomenon, the effect of giant magnetoresistance (GMR) was found in 1988 [8,9]. This is a drastic change in the electrical resistivity under an external magnetic field. The magnetic field induces a change in the relative orientation of the magnetic layers. The GMR effect allows to turn the information of a two-state magnetic system (parallel or anti-parallel representing 0 or 1) into an electrical one, or in a more abstract sense, to translate spin information into charge current information. Secondly, a GMR device can easily detect the direction of a magnetic field. This opened a huge market for sensor applications. A comprehensive review of experimental results with GMR devices is given in [10] and an overview on theoretical models applied is given in [11].

Soon after the discovery of GMR, experiments have been carried out in which the non-magnetic metallic spacer was replaced by a non-magnetic insulator. In this geometry spin-polarized electrons tunnel from one ferromagnetic layer through an insulating barrier into the second ferromagnetic layer, and again a strong dependence of the resistance upon the relative orientation of the magnetization was found. The effect is called the tunneling magnetoresistance (TMR) and the device is called a magnetic tunnel junction (MTJ). In contrast to GMR systems, TMR systems exhibit a large voltage drop across the MTJ and operate with small electrical currents. The large technological interest on these systems has initiated a large number of experimental as well as theoretical investigations to elucidate the microscopic origin of the phenomena. Theoretical models to describe TMR in connection with experimental results are presented in [12].

The very promising field connecting spin electronics and classical semiconductor technology arises from the easy control of charge density in these devices by means of doping and gate electrodes. Recently suggested or demonstrated devices, like the Datta-Das transistor [13] and the spin-valve transistor...